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Citation: [AIP Conference Proceedings](#) **370**, 589 (1996); doi: 10.1063/1.50816

View online: <http://dx.doi.org/10.1063/1.50816>

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# STRESS WAVE ATTENUATION IN SHOCK DAMAGED ROCK

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The attenuation of ultrasonic stress waves in samples of gabbroic rock subjected to shock loading in the 11 GPa range were studied. We determined the damage deficits,  $D_p$ , and attenuation coefficients,  $\alpha_p$ , for the samples with different damage deficits under dynamic strains of  $2 \times 10^{-7}$  and at frequencies around 2 MHz using ultrasonic pulse-echo method. A fit to the data yields the P-wave spatial attenuation coefficient versus damage deficit:  $\alpha_p = 40.9D_p - 30.5D_p^2$  (db/cm). Basing on the O'Connell-Budiansky theory, the relation between attenuation coefficient and crack density is given. The predictions of  $\alpha_p$  from Walsh's theory agrees well with the experiment results for the samples with different damage deficits.

## INTRODUCTION

The attenuation of stress wave in rocks is generally believed to be caused by internal friction between crack surfaces when stress wave propagates and induces differential motion along the usually present cracks (Born, 1941; Walsh, 1965). Generally, attenuation depends on stress amplitude and frequency, as well as, pressure, temperature and fluid saturation.

Experimental measurements of attenuation of stress waves in several rocks have been extensively studied since 1940's in the laboratory using different techniques over a wide-frequency range (Born, 1941; Jackson, 1969; Nur and Simons, 1969; Toksoz and Johnston, 1979; Winkler, 1982 etc.). All these studies concentrated on the relations between attenuation and parameters other than crack density induced velocity deficits. Because attenuation is directly related to crack density, research on influence of crack density on attenuation can provide detailed information about the mechanism of attenuation. The present study presents the first experimental data for the P-wave attenuation of gabbroic rock which are pre-damaged by shock waves using the ultrasonic pulse-echo method of Winkler et al (1982).

## EXPERIMENTAL TECHNIQUE

### Sample preparation

The rock studied was San Marcos gabbro which has been studied previously (Ahrens et al 1993; Rubin et al, 1991). The density of San Marcos gabbro is 2.87 g/cm<sup>3</sup>, and there is very low initial crack density.

Initially a large gabbro target with dimensions 200 × 200 × 150mm was impacted by a lead projectile at a velocity of 1.2 km/s, the projectile had a diameter in 7 mm and mass of 3 gm. The pressure of the shock wave in the target was estimated to be about 11 GPa at a radius of 0.35 cm and about 0.1 GPa at radius of 8cm from the impact site along the center-line of the impact using a power-decay relation and the impedance match method (Ahrens et al, 1987 and 1994).

The recovered target was cut into 1 cm cubes, with two surfaces being perpendicular to the impact axis. The 1 cm cubes were polished until the variation in sample thickness was less than 0.03 mm. Prior to measurement, the samples were placed in an oven under normal pressure at 100°C for 24 hours.

### Damage Deficits for P-wave

For the damage deficits, we follow the definition used in Grady et al (1987) and Ahrens et al (1994) which gives:

$$D_p = 1 - \left( \frac{C_p}{C_{p0}} \right)^2 \quad (1)$$

where  $D_p$  is the damage deficit for P-waves,  $C_p$  is the P-wave velocity measured for the damaged samples and  $C_{p0}$  is the intrinsic P-wave velocity for initial samples.

### Attenuation Coefficient

The ultrasonic experimental apparatus used in this work is similar to that developed by Winkler et al (1982) for the attenuation coefficient measurements as shown in Fig.(1).

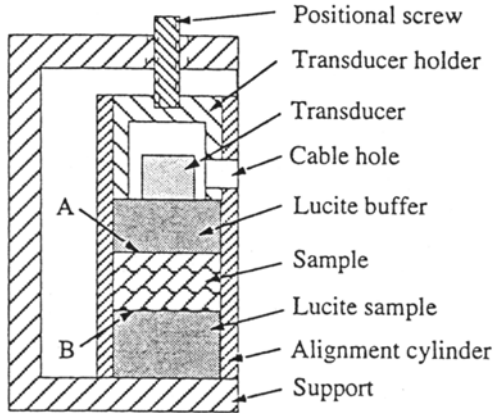


Fig.1 Measurement system

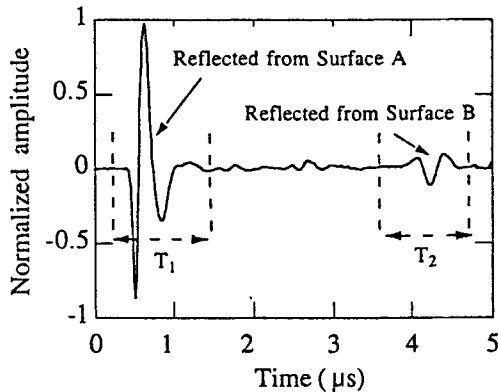


Fig.2 A typical ultrasonic record

Suppose that the reflecting and transmission coefficients of the surfaces between the buffer and sample are equal to that for plane-wave incidence as in Winkler et al (1982), the changing amplitude of the wave is then totally from intrinsic attenuation. Let  $R$  be reflection coefficient for the interface between the coupling buffer and sample and  $L/2$  be sample thickness,  $A(f)$  and  $B(f)$  be

the frequency-dependent amplitudes of the pulses reflected from the surface A and B (in Fig.1) of the sample, respectively. The attenuation coefficient obtained from the two reflected stress waves is expressed as (Winkler et al, 1982):

$$\alpha(f) = \frac{8.686}{L} \ln \left[ \frac{A(f)}{B(f)} (1 - R^2) \right] \quad (2)$$

where the unit of  $\alpha(f)$  is db/cm when the unit of  $L$  is cm and  $R$  is expressed as

$$R = \frac{C_p \rho - C_{pc} \rho_c}{C_p \rho + C_{pc} \rho_c} \quad (3)$$

where  $C_p$  and  $\rho$  are the P-wave velocity and the density of the gabbro sample measured, respectively.  $C_{pc}$  and  $\rho_c$  are the P-wave velocity and density of the coupling buffer (Lucite). From the ultrasonic measurement,  $C_{pc}$  is 2.68 km/s and  $\rho_c$  is 1.19 g/cm<sup>3</sup>.

A piezoelectric transducer (Panametrics, Model 102) is used as the pulse generator and the receiver. The transducer's driver is a Panametrics 5052UA pulser/receiver as shown in Fig.1. The recorded signals are used to calculate the magnitude of each frequency component of each pulse using Fast Fourier Transformation (FFT).

### RESULTS AND ANALYSIS

A typical signal recorded for the attenuation measurement is shown in Fig.2, in which the first signal is reflected from the surface A of the sample and the second from the surface B, and  $T_1$  and  $T_2$  are the data length used in the FFT. A typical result of spectral analyses is shown in Fig.3. It is found that most of energy of the stress wave generated by the transducer is concentrated in the frequency range between 1.5 and 3.5 MHz. Using the Eq.(2), the attenuation coefficients for the samples with differential damage deficits have been evaluated as shown in Figs. (4) and (5). From Fig.(4), we can see that the attenuation coefficients for the samples with different damage deficits increase approximately linearly with frequency. From Fig. (5), the relation between attenuation coefficient and damage deficits for 2 MHz can be expressed as

$$\alpha_p(\text{db/cm}) = 40.9 D_p - 30.5 D_p^2 \quad (4)$$

O'Connell and Budiansky (1974) established the relation between velocity and crack density as follows:

$$\left(\frac{C_p}{C_{p0}}\right)^2 = \frac{(1-\nu)(1+\nu_0)}{(1+\nu)(1-\nu_0)} \left(1 - \frac{16(1-\nu^2)\epsilon}{9(1-2\nu)}\right) \quad (5)$$

$$\frac{\nu}{\nu_0} = 1 - \frac{16\epsilon}{9} \quad (6)$$

where  $\nu$  and  $\nu_0$  are effective and intrinsic Poisson's ratio, respectively.  $\epsilon$  is crack density which is defined as  $N < a^3 >$  ( $N$  is the number of cracks per unit volume and  $a$  is the half-length of cracks).

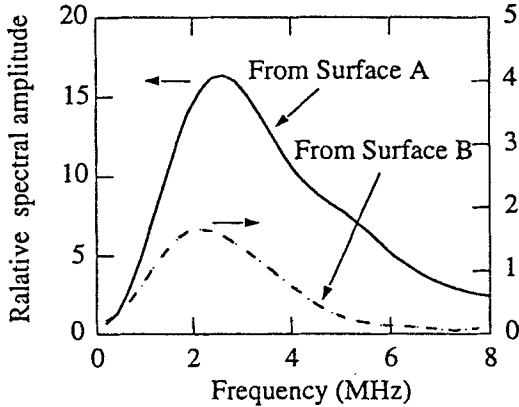


Fig.3 Typical spectral amplitude of signals

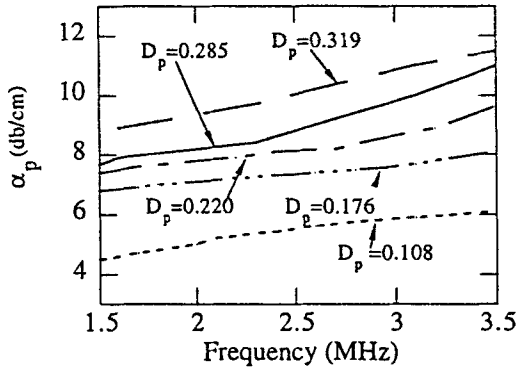


Fig.4 The experiment results of attenuation coefficient with frequency for samples with different damage deficits

From the definition of damage deficits, Eq.(1), and the relation between velocity and crack density, Eq.(7), the relation between  $D_p$  and  $\epsilon$  is approximately as :

$$D_p = 2.4\epsilon - 1.2\epsilon^2 \quad (7)$$

From Eqs. (4) and (7), the approximate expression relating  $\alpha_p$  to  $\epsilon$  is

$$\alpha_p = 96.1\epsilon(1 - 2.2\epsilon + 1.69\epsilon^2 - 0.4\epsilon^3) \quad (8)$$

Figure 6 presents the experimental results of attenuation versus crack density and the fitted curve. From results, it can see that rate of attenuation coefficient versus crack density decreases with crack density. This can be explained using the relations among attenuation coefficient, crack density and half-length. From the definitions of the attenuation coefficient and crack density, attenuation coefficient is related to the area of crack surface, this means  $\alpha_p \propto a^2$  therefore, from the definition of crack density, we have

$$\frac{\alpha_p}{\epsilon} = \frac{b}{a} \quad (9)$$

therefore, the ratio,  $\frac{\alpha_p}{\epsilon}$ , must decrease with increasing of crack density. The experimental results shows this in Fig.(6). If we suppose  $b$  is a constant, the average half-length of cracks can be estimated as shown in Fig.(7).

Basing on the frictional dissipation on crack surfaces sliding relative to one another during the passing of stress wave, Walsh (1966) developed an expression for the P-wave attenuation coefficient which can approximately be expressed as

$$\alpha_p = H f \epsilon \frac{K(1-\nu)(1-2\nu)}{K_0(1-2\nu)(1-2\nu_0)} \quad (10)$$

where  $H$  is considered to be a constant and  $f$  is frequency. Only one parameter,  $H$ , needs to be determined. If let  $\epsilon = 0.1$ , from Eqs. (6) and (8), the relation between  $K$  and  $K_0$  (O'Connell et al, 1974) and experimental results of attenuation coefficient,  $H$  is evaluated to be 60.74 db/cm for  $f = 2$  MHz.

The calculated results from Eq.(11) is shown in Fig.6. It is obvious that the results from Walsh's theory are in good agreement with the experimental results upon the fitting of  $H$  although the relation between  $\alpha_p$  and  $\epsilon$  is nonlinear. This result demonstrate that Walsh's theory can be used to evaluate attenuation coefficient in rocks with varying crack density.

## CONCLUSIONS

Some 20 samples of San Marcos gabbro cut from a shock loaded target are used to measure attenuation coefficients for different damage levels using the ultrasonic method. We used O'Connell and Budiansky's theory for crack density to relate crack density to the damage deficits. Walsh's theory (1966) was used to decide the attenuation coefficients of the samples with different crack density. Our main conclusions are

(1) The P-wave attenuation coefficient and the damage deficits is given by Eq.(4).

(2) Based on the O'Connell and Budiansky's theory, the relation between the crack density and attenuation coefficient can be expressed approximately as Eq.(8).

(3) Basing on Walsh's theory, we decided the variation of attenuation coefficient with crack density as shown in Fig(6).

**Acknowledgments:** This research is supported by NASA (NAGW-1941) and Phillips Lab. (F19628-95-C-0115). Contribution number 5571, Division of Geological and Planetary Sciences, California Institute of Technology. We thank Professor G. Ravichandran for the use of the ultrasonic apparatus.

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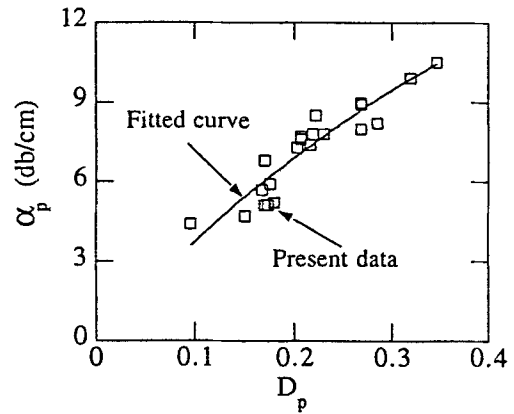


Fig.5 Relation between damage deficit and attenuation coefficient

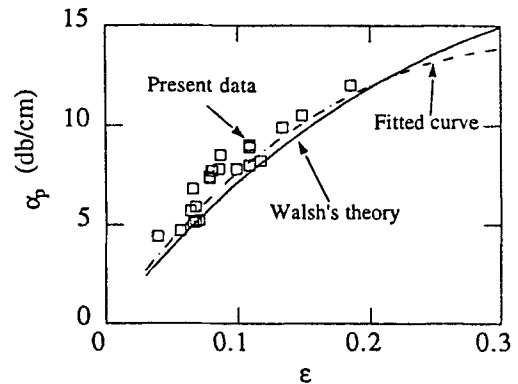


Fig.6 The relation between attenuation coefficient and crack density

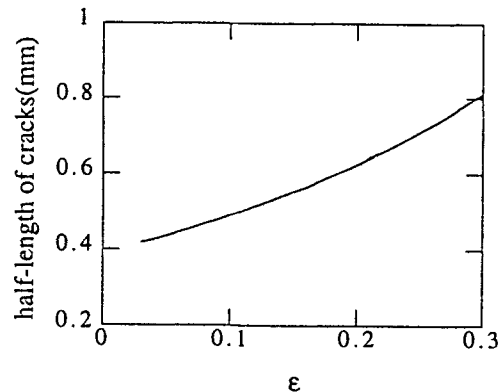


Fig.7 The estimated average half-length of cracks